

Brief description of the flavor-changing neutral scalar interactions at two-loop level

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Abstract. In this letter we show a general description about flavor-changing neutral currents (FCNC) mediated by scalars. The analysis is extended at two-loop level for the Two-Higgs Doublet Model type-III because others models have strong constraints on its parameters, even at high orders of the perturbation. For this letter we focus on the standard model, calculating the amplitude for the $h \rightarrow \gamma\gamma$ process and discussing the results briefly.

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1. Introduction

The standard model (SM) of particles has awesome results: the experimental measurements and the theoretical results match very well. The observables are calculated using the Feynman diagrams. For instance, to obtain the decay width or the cross section, we need the Lagrangian or the Feynman rules (vertices and propagators of the model). In general, the SM extensions increase the vertex and propagators number. SM extensions are built to explore New Physics (NP) and describe unexplored phenomena. NP includes proposals as beyond standard model (BSM), it involves new particles, new interactions and new dimensions; for explaining or responding to the unsolved questions.

We can extend the gauge, fermion or scalar sector. Focusing on the last one, the simplest possibility to extend the SM is the Two-Higgs Doublet Model (THDM), which introduces a doublet scalar field plus the SM doublet. Theoretical motivations to enlarge the scalar sector could explain, e.g., the CP violation and the flavor-changing neutral currents (FCNC) in the gauge sector [1].

The rich phenomenology for the THDM has been widely studied by different theoretical and phenomenological groups. Some reports show interesting results for the Flavor-changing (FC) [2–4], an analysis at one-loop level for the pseudoscalar appears in [5], and at two loops in the lepton sector is found in [6]. Several experimental reports are dedicated to the exotic physics searching for new particles coming from a variety of models [7–13].

The purpose of this paper is to further explore the FC mediated by scalar bosons at loop-level. We were inspired by the recent experimental results (e.g., refs. [14, 15]) and for theoretical

motivations on the scalar sector. We are aware of the strong constraints on loop-level and its low contributions in the processes and, even, in the loop-level with FC mediated by scalar bosons; but we shall expect a more general description for the neutral scalar interactions and their constraints [16, 17], which are so-called flavor-changing neutral scalar interactions (FCNSI), though they can be found as flavor-changing scalar currents (FCSC). We shall analyze the amplitudes at loop-level to have a new perspective for these processes. As known, GIM mechanism controls the neutral currents at tree-level. It means that processes with flavor-changing mediated by vector bosons are constrained because of the orthogonality of the CKM matrix [18, 19]. We would like to know whether it is similar for flavor-changing mediated by scalar bosons.

Our goal is to provide an analysis on the equation of the amplitud at two-loop level in general and for the SM and THDM to explain the FCNSI and its contribution, if any, for these kind of processes. We are motivated by the next generation of colliders where it would be possible to explore the couplings in the $\gamma\gamma$ -processes [20]. We will use the THDM-III because it has flavor-changing neutral current (FCNC) transitions mediated by scalar bosons even at tree-level. We expect that this document be the first of a series of papers about the flavor-changing and scalars at high-loop level.

We organize this paper as follow: section 2 describes the lagrangian for the model and its systematic implementation by the computer. In section 3, we show the results at two-loop level for the amplitude and in section 4 we leave a brief discussion and conclusions.

2. Model

There are two versions of THDM, labeled as type I and type II, with invariance under Z_2 discrete symmetry which ensures CP conservation in the scalar sector. In the first case, all quarks acquire mass through one doublet whereas in type II one doublet gives mass to the up-type quarks while the other doublet gives mass to the down-type quarks. In the type III both doublets simultaneously give masses to all quarks. In the THDM-III, it is possible to have flavor-changing considering parameters, which may induce FCNSI; those parameters are free. There is FCNSI as long as the diagonalization of the fermion mass matrices does not ensure the diagonalization of each of the Yukawa matrices [1, 21].

2.1. Lagrangian for the THDM

For the THDM-III, the general potential is given by [3]:

$$\begin{aligned} V(\Phi_1\Phi_2) = & \lambda_1(\Phi_1^\dagger\Phi_1 - v_1^2)^2 + \lambda_2(\Phi_2^\dagger\Phi_2 - v_2^2)^2 + \lambda_3\left[(\Phi_1^\dagger\Phi_1 - v_1^2) + (\Phi_2^\dagger\Phi_2 - v_2^2)\right]^2 \\ & + \lambda_4\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right] + \lambda_5\left[Re(\Phi_1^\dagger\Phi_2) - v_1v_2\right]^2 \\ & + \lambda_6\left[Im(\Phi_1^\dagger\Phi_2)\right]^2 \end{aligned}$$

where λ_i are real, v_i 's are the vaccuum expectation values and Φ_i 's are the Higgs doublets.

The Yukawa sector for the THDM-III is

$$\mathcal{L}_{YS}^{THDM-III} = Y_1^u \bar{Q}_L^0 \tilde{\Phi}_1 u_R^0 + Y_2^u \bar{Q}_L^0 \tilde{\Phi}_2 u_R^0 + Y_1^d \bar{Q}_L^0 \Phi_1 d_R^0 + Y_2^d \bar{Q}_L^0 \Phi_2 d_R^0 + h.c.$$

where Y_i are the Yukawa couplings and $Q_L^0 = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$, $\bar{Q}_L^0 = (\bar{u}_L, \bar{d}_L)$, $\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1 \end{pmatrix}$, $\Phi_2 =$

$\begin{pmatrix} \phi_2^\pm \\ \phi_2 \end{pmatrix}, \tilde{\Phi}_j = i\sigma_2 \Phi_j^* = \begin{pmatrix} \phi_j^* \\ -\phi_j^\mp \end{pmatrix}$ and $\phi_i = \frac{1}{\sqrt{2}}(v_i + \phi_i^0 + i\chi_i)$. Then we obtained,

$$\mathcal{L}_{YS}^{THDM-III} = \mathcal{L}_{YS-NS}^{THDM-III} + \mathcal{L}_{YS-CS}^{THDM-III} + h.c.$$

where the neutral-sector is

$$\mathcal{L}_{YS-NS}^{THDM-III} = Y_1^u \bar{u}_L \phi_1^{0*} u_R + Y_2^u \bar{u}_L \phi_2^{0*} u_R + Y_1^d \bar{d}_L \phi_1^0 d_R + Y_2^d \bar{d}_L \phi_2^0 d_R \quad (1)$$

and the charged-sector is

$$\mathcal{L}_{YS-CS}^{THDM-III} = +Y_1^u \bar{d}_L (-\phi_2^-) u_R + Y_2^u \bar{d}_L (-\phi_1^-) u_R + Y_1^d \bar{u}_L \phi_1^+ d_R + Y_2^d \bar{u}_L \phi_2^+ d_R. \quad (2)$$

We will use the neutral sector for this paper. In this sector the interaction between fermions and scalar is given by the Yukawa couplings (Y_f); in general, this is

$$g_{hff} \sim Y^f \sim m_f \quad (3)$$

where g_{hff} is the coupling, which represents the vertex between the Higgs and pair of fermions. In the SM the coupling is given by

$$g_{hff}^{SM} = Y_{SM}^f = \sqrt{2} \frac{m_f}{v} \quad (4)$$

where m_f is fermion mass and v is the vacuum expectation value (VEV). For the THDM, after the spontaneous symmetry breaking the mass matrix is given by

$$m_f = \frac{1}{\sqrt{2}} (v_1 Y_1^f + v_2 Y_2^f) \quad (5)$$

where we have two VEV's v_1 and v_2 , which are relationated by: $\frac{v_2}{v_1} = \tan \beta$. In a general form, the eq. (5) is non-diagonal, and it can be made by:

$$(U_L^f)^\dagger m_f (U_R^f) = \tilde{m}_f \quad (6)$$

It is important to note that the widetilde over the quantities means the flavor basis. Besides, in general, U is ortogonal and Y^f could be complex. So it is possible to have mixing between the mass (fermions) eigenstates at tree level. Considering the Yukawa matrices Hermitian, the mass eigenstates are

$$f = U_f^\dagger f' \quad (7)$$

where f can be u, d -type quarks and l leptons. Then the mass matrix is given by

$$\tilde{m}_f = \frac{1}{\sqrt{2}} (v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f) \quad (8)$$

where, $\tilde{Y}_i^f = U_L^\dagger Y_i^f U_R$.

In order to reduce the free parameters, one can rewrite the eq.(5) as:

$$\tilde{Y}_1^f = \sqrt{2} \frac{m_f}{v \cos \beta} - \tilde{Y}_2^f \tan \beta. \quad (9)$$

Sometimes Yukawa couplings are defined in terms on $\tilde{\chi}_{ij}$ parameters [5]; namely,

$$\tilde{Y}_{ij}^f = \sqrt{2} \frac{\sqrt{m_i m_j}}{v} \tilde{\chi}_{ij}^f, \quad (10)$$

where m_i and m_j are the fermion masses, and $\tilde{\chi}_{ij}^f$ are free parameters. This specific pattern is known as Cheng & Sher ansatz [22]. Through this mechanism it is possible to have FCNSI at tree-level. This relation has been used in different papers; e.g. [2, 5, 24].

In the next subsection we show the scheme to obtain the amplitude.

2.2. Methods

We calculate the amplitude at two-loop level. We represent the scheme in fig. 1.

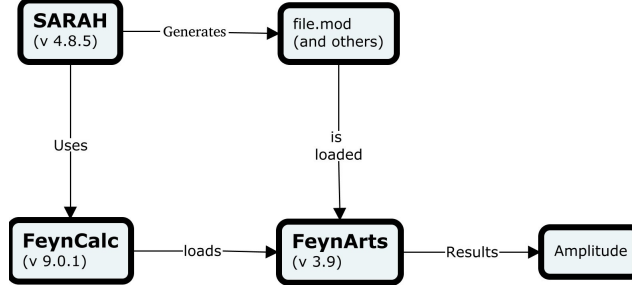


Figure 1. This scheme shows the path to follow for obtaining the amplitude at two-loop level, using SARAH [25–27], FeynCalc and FeynArts [28]. We implemented the THDM-III and FV and use different commands to exclude field points, isolating a process with Higgs boson, which has $m_h \sim 126$ GeV, and mediated by virtual Higgs boson.

Next section shows the results for the $h \rightarrow \gamma\gamma$ process at two-loop level, considering the flavor-changing mediated by a SM-like scalar boson.

3. Results

We implemented the THDM-III with the flavor-changing in SARAH for the process represented by fig. 2.

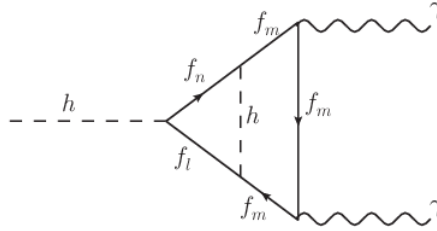


Figure 2. The Feynman diagram for the process $h \rightarrow \gamma\gamma$ at two-loop level; note FC in the loop mediated by the scalar. We do not draw the adjoint process.

The amplitude is given by

$$\mathcal{M}_2(\phi \rightarrow V'V) = -\frac{i}{256\pi^8 m_h^{12} \prod_{\lambda=1}^6 P_\lambda} \text{Tr}(M_2^{\mu_1\mu_2}) \epsilon_{\mu_1}^*(p_2) \epsilon_{\mu_2}^*(p_3) \quad (11)$$

where the product of the propagators is

$$\prod_{\lambda=1}^6 P_\lambda = (r_{q_1} - r_l)(r_{q_2} - r_m)(r_{p_3\bar{q}_2} - r_m)(r_{q_1q_2} - 1)(r_{p_2p_3q_1} - r_n)(r_{p_2p_3\bar{q}_2} - r_m) \quad (12)$$

with $r_i = \frac{m_i^2}{m_h^2}$, $r_{p_i\bar{p}_j} = \frac{(p_i - p_j)^2}{m_h^2}$, $r_{q_iq_j} = \frac{(q_i + q_j)^2}{m_h^2}$, $r_{p_ip_jq_k} = \frac{(p_i + p_j + q_k)^2}{m_h^2}$ and $r_{p_ip_j\bar{q}_k} = \frac{(p_i + p_j - q_k)^2}{m_h^2}$. p_1 is the momentum for the scalar boson, $p_{2,3}$ are the momentum of the particles in the final

state and $q_{1,2}$ are the momentum for the loops. The tensorial amplitud is

$$\begin{aligned}
M_2^{\mu_1\mu_2} = & \kappa^{\text{SM}} (m_m + \gamma_{\nu_1} P_{q_2\bar{p}_2\bar{p}_3}^{\nu_1}) \gamma^{\mu_1} (P_L + P_R) \\
& (m_m + \gamma_{\nu_2} P_{q_2\bar{p}_3}^{\nu_2}) \gamma^{\mu_2} (P_L + P_R) \\
& (m_m + \gamma_{\nu_3} q_2^{\nu_3}) (P_L + P_R) \\
& (m_l - \gamma_{\nu_4} q_1^{\nu_4}) (P_L + P_R) \\
& (m_n + \gamma_{\nu_5} P_{\bar{p}_2\bar{p}_3\bar{q}_1}^{\nu_5}) (P_L + P_R)
\end{aligned} \tag{13}$$

where $\kappa^{\text{SM}} = (-ie)^2 \left(-\frac{iem_f}{2M_W S_W} \right)^3$ and $P_{q_2\bar{p}_2\bar{p}_3}^{\nu_1} = (q_2 - p_2 - p_3)^{\nu_1}$, $P_{q_2\bar{p}_3}^{\nu_2} = (q_2 - p_3)^{\nu_2}$, and $P_{\bar{p}_2\bar{p}_3\bar{q}_1}^{\nu_5} = (-p_2 - p_3 - q_1)^{\nu_5}$. In eq. (13) is possible to reduce the $(P_R + P_L)$ terms, however these could contain the model-dependent parameters. It is shown simply the general expression for the SM, and the results for the THDM will be reported soon elsewhere.

4. Discussion and conclusions

The discovery of the Higgs boson and exploration of its properties generate great interest in the scientific community. Theoretically, there are challenges to calculate at two- or multi-loop level associated to ultraviolet, infrared and mass singularities. Besides the integration for multi-loop, considering massive or, maybe, non-scalar integrals could also be awkward calculation. Several technical calculations at one-loop have been developed [29–31], even there are some numerical methods to calculate at this level [32–34]; however there are unexplored models with FCNSI at high-loop level. We expect that high-loop level studies can be interesting tests for the NP.

In this paper, we discuss $h \rightarrow \gamma\gamma$ decay. This kind of process may be explored by the future generation of colliders. The enhanced measurements could show more information about the FC mediated by scalars and the Yukawa couplings.

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